Physics of laser ablation and the quest for maximum CE

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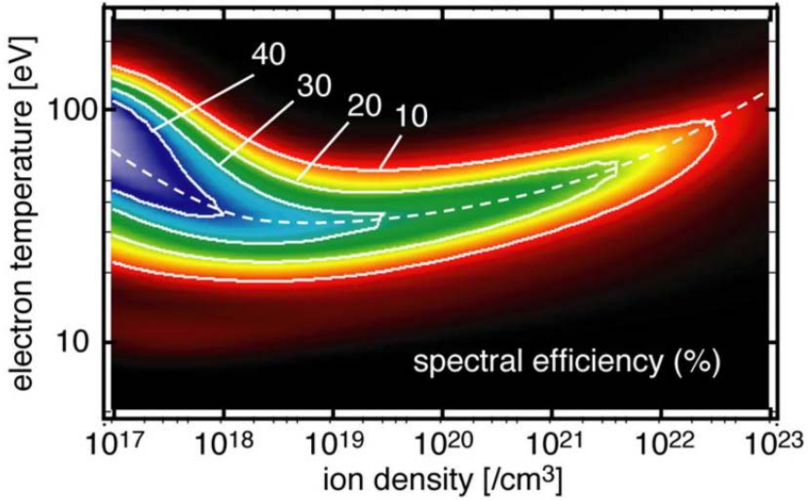
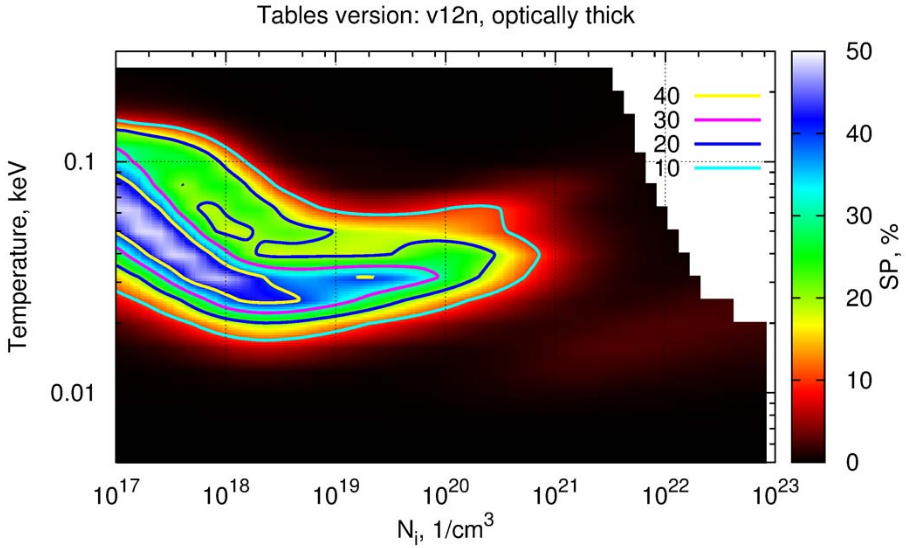
Spectral purity (SP) of the EUV emission from Sn plasmas

$$\mathbf{SP} = \frac{\text{Emission power into the 2\% band at 13.5 nm into } 4\pi}{\text{Total EUV emission power into } 4\pi}$$

<u>SP inferred from the atomic physics (Sn plasma emissivity):</u>



K.Nishihara et al., Proc. SPIE 6921 (2008)

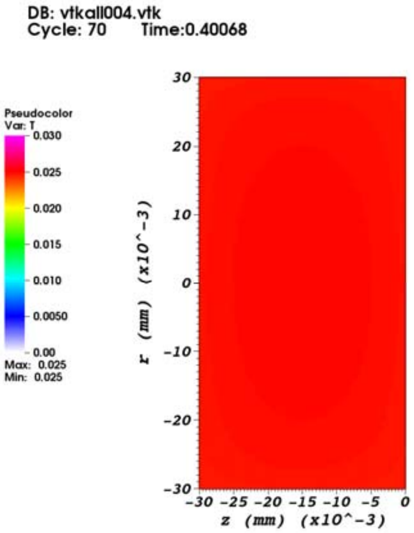


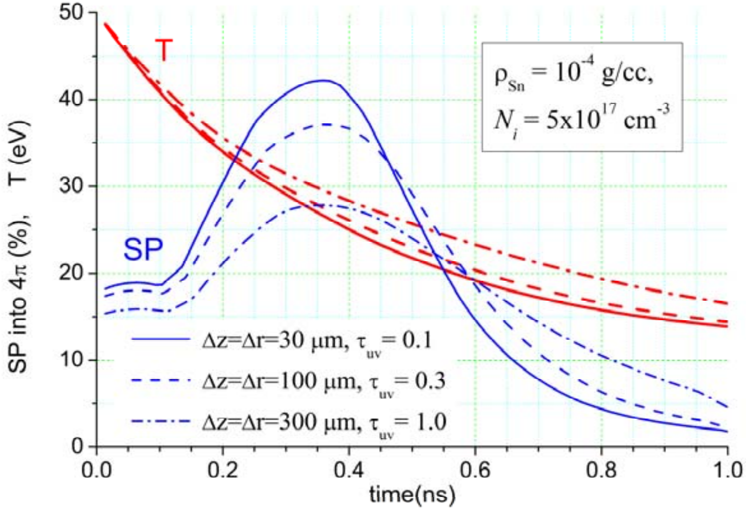
KIAM (V.Novikov, A.Solomyannaya, A.Grushin et al., 2012)

SP degradation due to self-absorption in band (RALEF-2D)

A static Sn-plasma cylinder cools down due to spectral radiative energy transport.

<u>Initial Sn-plasma state:</u> $\rho_0 = 10^{-4}$ g/cc ($N_i = 5 \times 10^{17}$ cm^{-3}), $T_0 = 50$ eV

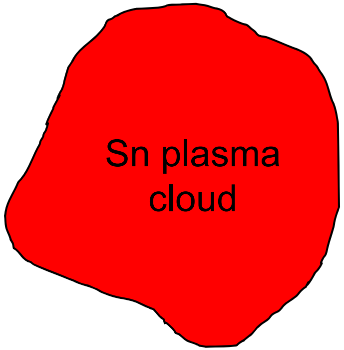




<u>What is learned</u>: (i) the peak spectral purity is ~ 42%,
(ii) the timescale of thermal inertia is ~ 0.5 ns,
(iii) the optimum size of the EUV emitting region is ≤ 100μm.

Absolute theoretical maximum of CE

$$\mathbf{CE} = \frac{\text{Emission power into the 2\% band at 13.5 nm into } 2\pi}{\text{Total power of the heating laser}}$$



L

$$\tau_{uv} = k_{uv}\, L$$

If a plasma cloud with SP≈40% could be maintained in *a static state* at no cost, and if the radiation losses were compensated by laser heating at a 100% efficiency,

$\Rightarrow$ one would obtain $\boxed{\text{CE} \approx 20\%}$!

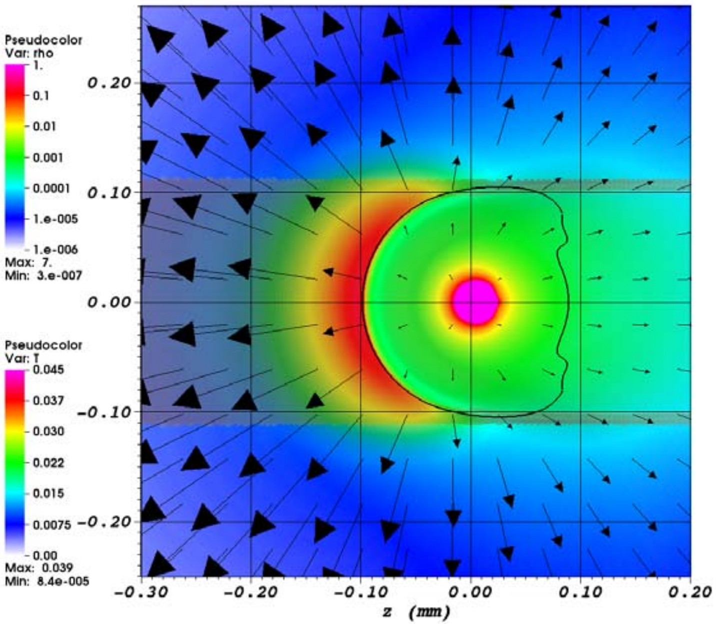
Optimum Sn-plasma parameters for the "working" zone:

- density: $N_i \le 10^{18}$ $(N_e \le 10^{19})$ cm^{-3} [CO_2 laser!]
- temperature: T = 30 – 40 eV
- size: $\tau_{uv} \le 0.1 \div 0.3$ [SP $\rightarrow$ 1.5% as $\tau_{uv} \rightarrow \infty$]

$$k_{uv} \approx 70 \left(\frac{n_e}{10^{19} cm^{-3}}\right)\left(\frac{30\ \text{eV}}{T}\right)^{3.5}\ \text{cm}^{-1}$$ [Novikov *et al.*, 2012]

Statement of the problem

Question addressed: **how closely can one approach CE=20% under realistic conditions?**



Once *the static plasma* is excluded as unrealistic, the best close to reality theoretical idealization appears to be a steady ablation plasma flow.

To ensure the main-pulse (MP) laser access to the “working” zone, the plasma flow must have a diverging pattern $\Rightarrow$ in this study we concentrate on <u>a steady quasi-spherical ablation from a spherical droplet</u>.

For more details see [M.Basko, Phys.Plasmas, **23**, 083114, 2016].

Optimization tasks

The general optimization problem for maximum CE can be split into two separate tasks:

Task 1: find the maximum possible CE for a preconditioned Sn density profile $\Rightarrow$ maximum possible instantaneous CE !

Task 2: find the maximum possible steady-state CE for the self-consistent (i.e. consistent with a steady MP laser pulse) density profile.

General guidelines for maximizing CE:

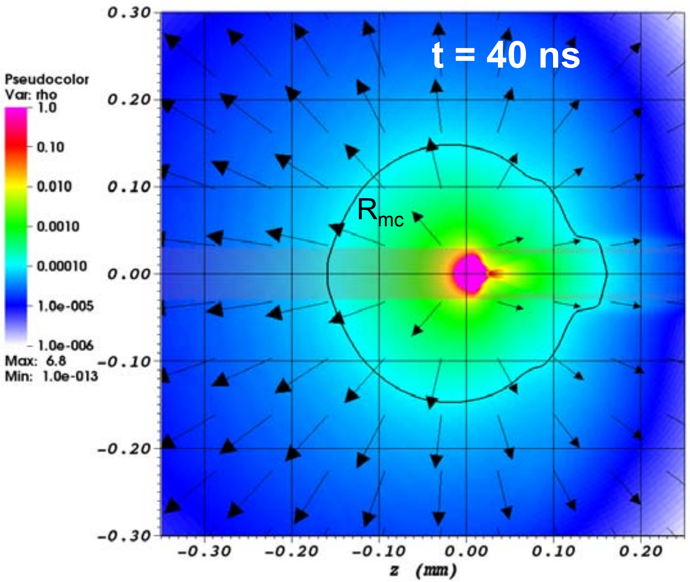
i. The MP laser pulse must be fully absorbed in the ablated plasma $\Rightarrow$ no steep gradients of n_e can be tolerated!

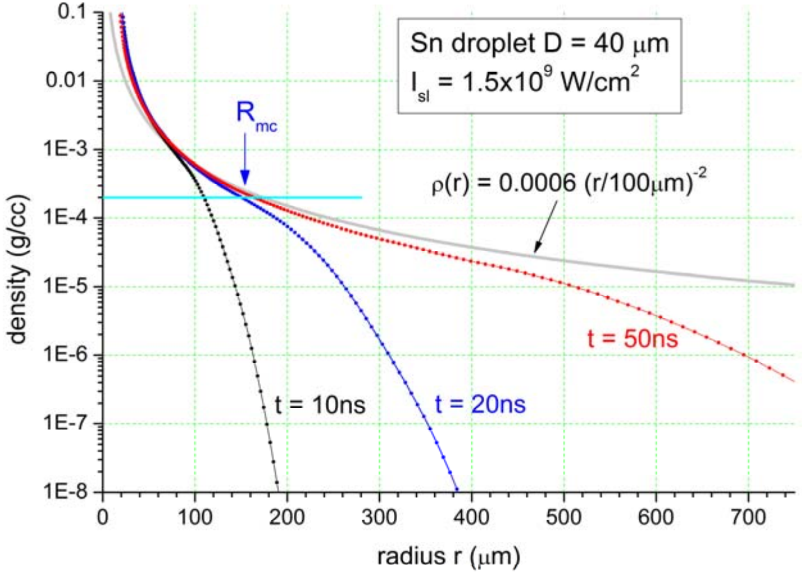
ii. As much as possible of the MP energy must be absorbed near the optimum temperature $T \approx 30 \div 40$ eV where the SP peaks.

$\Rightarrow$ **The "working" zone, where most of the MP is absorbed, must be fairly uniform in what concerns the n_e and T distributions.**

Task 1: density profile preconditioned by a "slave" laser

One of the ways to generate a smooth quasi-spherical flow might be to employ an independent short-wavelength "slave" laser at a low power level [Nishihara et al., Proc. SPIE 6921, 2008]**.**





After about 30–50 ns, the radial density profile stabilizes at $\rho \propto r^{-2}$!

Task 1: optimization strategy

Once the MP laser (λ_{ml} = 10.6 μm) is fixed, we are left with only two independent parameters to perform the full optimization, namely, with

- the spatial scale $\boldsymbol{R_{mc}}$ of the preconditioned density profile

$$\boxed{n_e(r) = n_{mc}\left(\frac{R_{mc}}{r}\right)^2,} \qquad n_{mc} = \text{the MP critical density;} \tag{1}$$

$$R_{mc} \approx R_{dr}{}^{0.63}\lambda_{ml}\lambda_{sl}{}^{-0.75}I_{sl,9}{}^{-0.08}\ [\mu m], \qquad R_{dr} = \text{droplet radius in μm;}$$

- the intensity $\boldsymbol{I_{ml}}$ of the MP, which controls the temperature $\boldsymbol{T}$ in the “working” zone

$$T \propto (\lambda_{ml}I_{ml})^{0.4}, \qquad \text{[Basko et al., Phys. Plasmas, } \mathbf{22}\text{, 053111, 2015]}$$

The full optimization of $\mathrm{CE} = \mathrm{CE}(I_{ml}, R_{mc})$ has been performed with the 2D RHD code RALEF.

The role of self-absorption in band

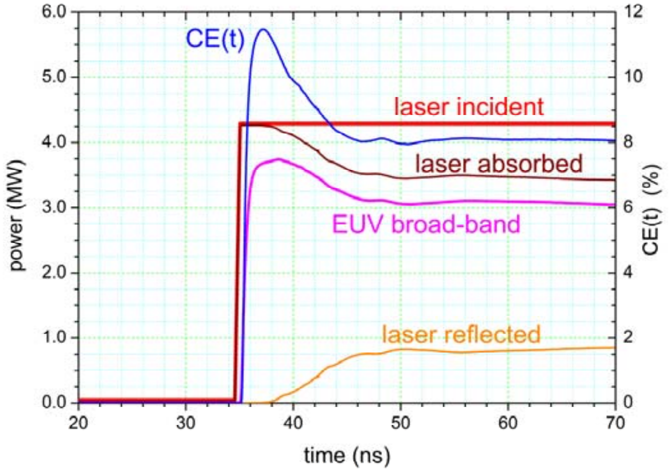
- A preferred optimum T value $\Rightarrow$ $\mathbf{CE} = \mathbf{CE}(I_{ml}, R_{mc})$ has a maximum versus I_{ml} (for each R_{mc});
- Interplay between the laser (τ_{ml}) and the in-band (τ_{uv}) absorption $\Rightarrow$ $\mathbf{CE} = \mathbf{CE}(I_{ml}, R_{mc})$ has a maximum with respect to R_{mc} $\Rightarrow$ there is an optimum EUV source size!

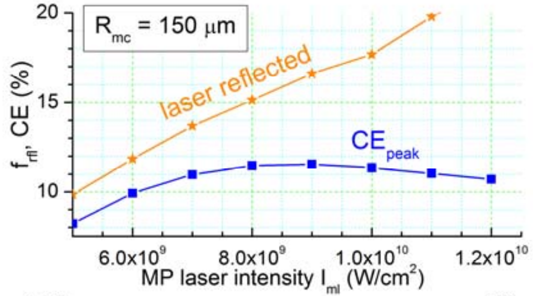
$$\frac{\tau_{uv}}{\tau_{ml}} \approx \frac{36}{z_i \ln \Lambda_{ml}} \left(\frac{30\text{eV}}{T}\right)^2 \left(\frac{R_{wz}}{R_{mc}}\right)^2 \approx (0.3 \div 0.5) \left(\frac{R_{wz}}{R_{mc}}\right)^2 \qquad (2)$$

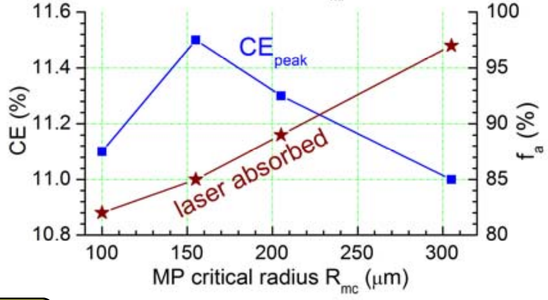
- For too small R_{mc} the **CE** drops because $\tau_{ml} << 1$, the radius of the “working” zone $R_{wz} = R_{mc}$, and the MP laser is poorly absorbed (mostly reflected).
- For too large R_{mc} we have $\tau_{ml} \sim 1$, $R_{wz} >> R_{mc}$, and the **CE** drops because $\tau_{uv} >> 1$ and the in-band emission is quenched by the self-absorption.
- The **CE** is maximum at $\tau_{ml} \approx 0.5$ and $R_{wz} \approx R_{mc}$, that is when the “working” zone is adjacent to the critical surface of the MP.

Optimization results for Task 1

CO_2 MP turned on at $t = 35$ ns







Task 1: **on a preconditioned ρ-profile,** **maximum CE = 11.5%.**

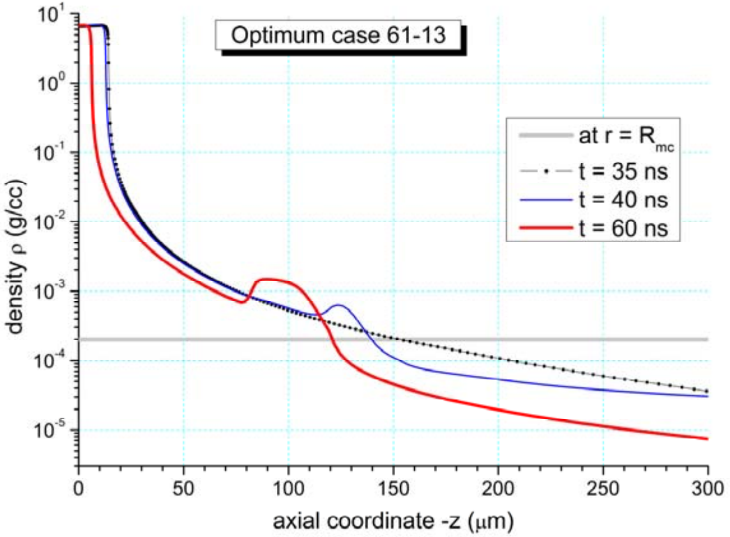
Causes of degradation from 20%: (i) about 2.5% – lost as the kinetic energy of the plasma flow;

(ii) the rest – due to the non-uniformity of T across the "working" zone and because of the in-band reabsorption.

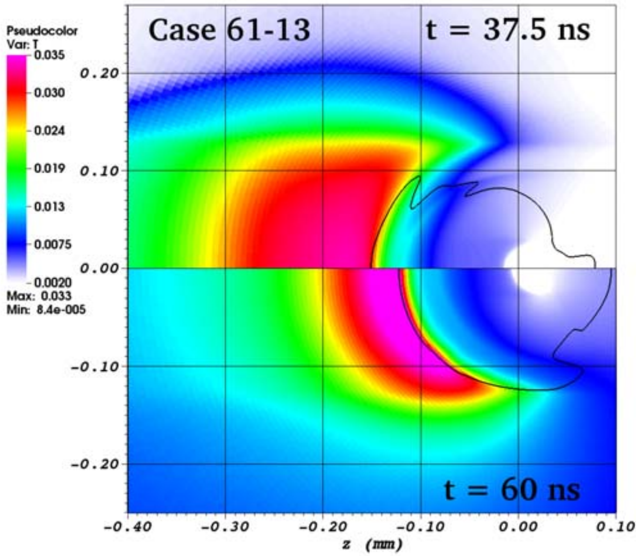
Task 2: self-consistent ablation density profile

Once turned on, the MP laser deforms the preconditioned density profile – the result being a higher laser reflection and a smaller CE.

Radial density profiles



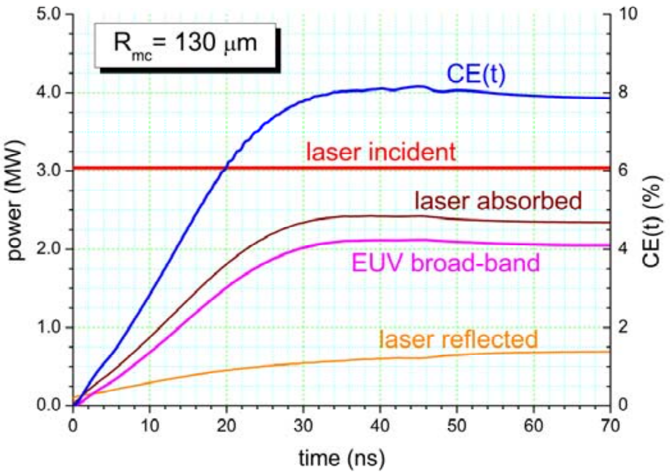
2D temperature distribution

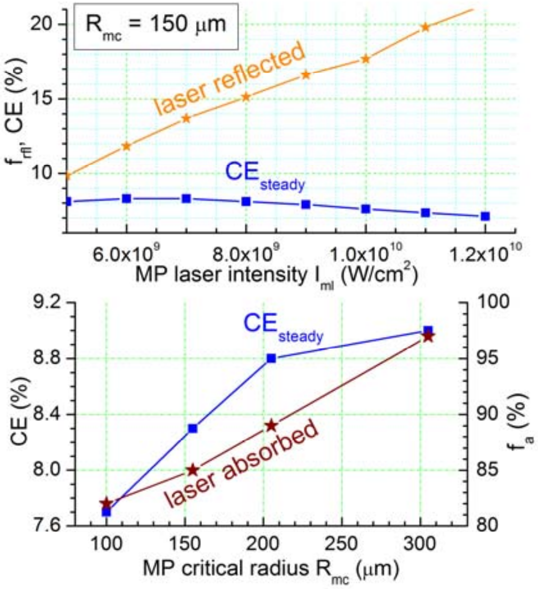


The optimization strategy remains the same as in Task 1 !

Optimization results for Task 2

CO_2 MP only (no "slave" laser)





Task 2: **with the self-consistent ρ-profiles, maximum CE = 9.0%.**

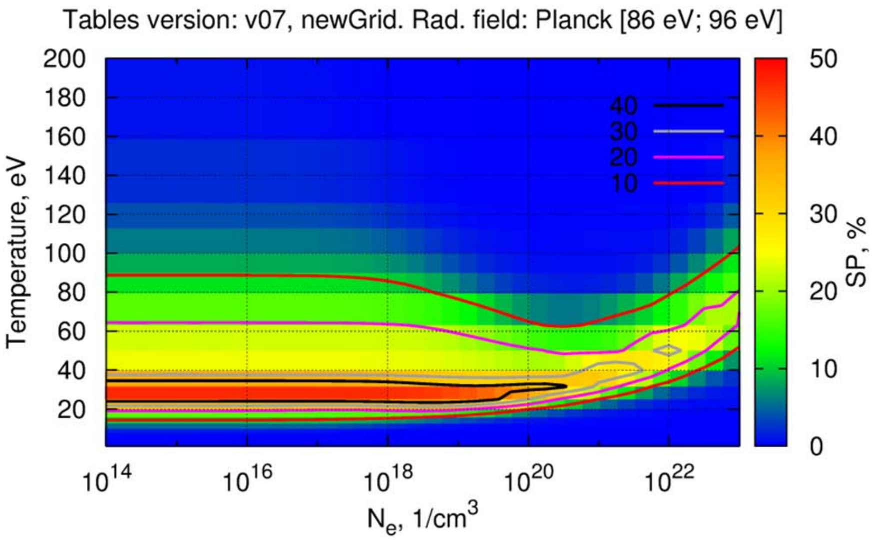
At a practically 100% laser absorption, the degradation of CE from 20% to 9% is mainly caused by a combination of self-absorption and temperature non-uniformity across the laser-absorption zone.

Conclusions

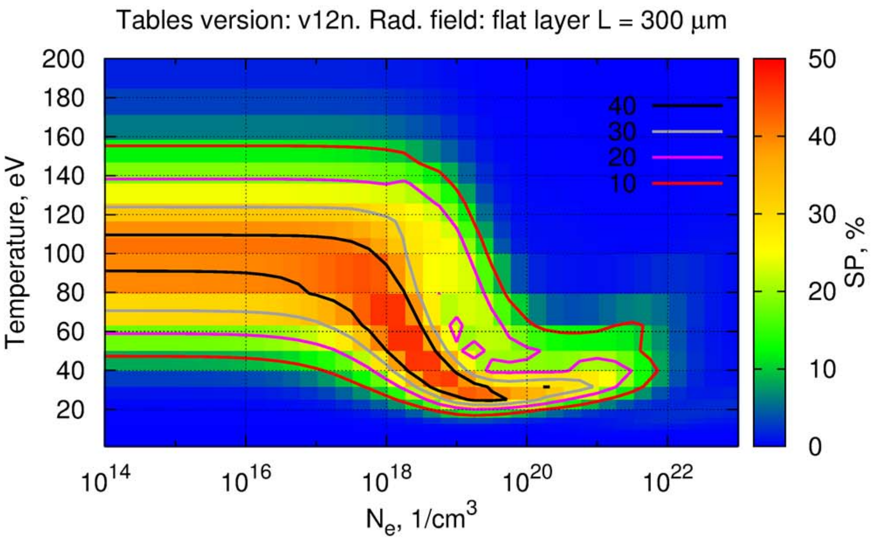
- For a fixed wavelength λ_{ml} of the MP laser, full optimization of CE under the conditions of steady-state laser ablation is equivalent to a two-parametric study with respect to the MP intensity $\boldsymbol{I_{ml}}$ and the plasma flow scale $\boldsymbol{R_{mc}}$.
- Fully optimized realistic CE values from the Sn ablation plasmas (11.5% in the transient peak, and 9% in the steady state) are still well below the absolute theoretical maximum of 20% suggested by the atomic physics – primarily due to a combined effect of the reabsorption in band, and non-optimal temperature profile imposed by the laser absorption physics.
- For sufficiently large values of λ_{ml} (like that of the CO_2 laser), the fully optimized CE becomes insensitive to λ_{ml} (because of saturation of the peak SP at low densities).

Appendix: SP from different KIAM opacity tables

Partially LTE: black-body in 10% around 13.5 nm



CRE with spectral leakage from a 300-μm Sn layer



Courtesy of A. Grushin, June 2016.